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DISCUSSION OF APPLICATION OF ELECTRONIC FLOW ROUTING ANALOG

(*Published in June, 1952*)

By Alfred J. Cooper, C. O. Clark, and Max A. Kohler

HYDRAULICS DIVISION

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DISCUSSION

ALFRED J. COOPER,[8] A. M. ASCE.—Hydrologists and hydraulic engineers concerned with open channel flow are indebted to the author and his colleagues for developing an electronic stream-flow routing analog that utilizes the well-known mathematical relationship for reach storage expressed by Mr. McCarthy[9,4] in the Muskingum method. Mr. Kohler has indicated that the design of this type of router can probably be modified to adapt it to more complex equations of storage than that used in the Muskingum method. This fact should make it a valuable addition to the profession.

Considering this device for what it can do, even with the deficiencies of the equation upon which it is based, it reveals certain distinct advantages compared to present methods of analytically routing stream flows. Analytical routing procedures are extremely laborious. Any simplification of the mathematical approach, as by an electrical analogy, is a great economy in time and labor. In addition, the analog is simple in design and operation, relatively low in cost, and produces results faster than existing methods and with an accuracy equal to, or better than, other methods. It has the distinct advantage over routing by certain periods of time in producing a continuous hydrograph. It is better than other routing devices in that adjustments for the major variables of different reaches or basins are simple to make—merely by the turning of dials. Furthermore, the analog can be used to determine reach flow-storage data, if desired, by a simple trial-and-error determination of K-values and x-values. The advantage of the electronic analog over a mechanical routing analog is in its ease of preparation for routing. Whereas mechanical devices can function very accurately, they require considerable time in preparation for routing a particular reach. As a result, they become economical only when there is a large volume of routing to be performed for that reach.

Applications to Multiple-Purpose Reservoir Operation.—In the daily operation of a multiple-purpose reservoir system such as the Tennessee Valley Authority (TVA), there are certain distinct applications of this analog. A continuous hydrograph of natural stream flow at several key points can be maintained with a minimum of time and personnel. This flow is then available for guidance in operation and for comparing the effects of alternate regulation combinations. The analog could aid materially in predicting inflows into tributary reservoirs and runoff from local areas between main river projects by the routing of effective rainfall. It could solve the problem of predicting crest flows and stages at critical points such as towns and cities on small creeks and rivers which are unregulated by the reservoir system, yet present flood problems. Such streams require a warning system that is rapid enough

NOTE.—This paper by Max A. Kohler was published in June, 1952, as *Proceedings-Separate No. 135*. The numbering of footnotes in this Separate is a continuation of the consecutive numbering used in the original paper.

[8] Head, Procedures Development Sect., Hydr. Data Branch, TVA, Knoxville, Tenn.

[9] "The Unit Hydrograph and Flood Routing," by G. T. McCarthy, unpublished manuscript presented at the Conference of the North Atlantic Div., Corps of Engrs., War Dept., June, 1938.

[4] "Engineering Construction—Flood Control," by G. T. McCarthy, The Engineer School, Ft. Belvoir Va., 1940, pp. 147–156.

to be useful, needs the minimum of personnel and money for its execution, and yet should not interfere materially with the main task for the river-control organization—that is, the water-control operations of the reservoir system. A further use could be the determination of the transformation of waves generated by fluctuations of discharges at dams. This use would permit chronological forecasts of flows and stages downstream to serve as the basis of water-supply purification, and it would furnish minor navigation information such as the accessibility of islands.

Deficiencies of Router in Multiple-Purpose Reservoir Operations.—From a water-control point of view, the TVA is singularly in a situation in which, eventually, the entire United States will find itself with the trend toward regulation of rivers for single or multiple purposes. The TVA is faced with the necessity of operating a regulated stream in which many critical river points do not have a simple stage-discharge relation. In its present design, this analog is not adaptable to the solution of problems involving more than the three variables of inflow, outflow, and storage. With controlled outflow a fourth variable appears in the picture—backwater, or slope, effect. This variable occurs also in natural streams affected by backwater, as in the Tennessee River below Pickwick Landing Dam even prior to the impoundment of Kentucky Reservoir, in the reach below Kentucky Dam, and in the Ohio River. The graphical and analytical routing procedures presently used by the TVA involve these four variables.

It is desirable that a circuit be devised in which some of the factors now used as constants could be varied during the operation of the analog to simulate the conditions found in open channel flow. Even with the present circuit applicable to most cases of uncontrolled outflow, it would increase the accuracy of the results if the factors K and x could be varied since these items, usually, do not remain constant throughout the range from low to flood flows. Investigations reported in 1944[10] indicated clearly that there are different times of wave travel; hence there is a variation in K-value over a wide range of stage in a given reach. Preliminary studies of the value of x for the mid-August and late August, 1940, floods on the Holston and French Broad rivers just above Knoxville indicate that a variation of x is encountered, which is not only dependent on the distribution of runoff in the area but also, to a minor degree, in the range of flows occurring in the mid-August flood.

The use of an empirical function such as Eq. 5 to define the storage, in the cases where the Muskingum equation apparently did not serve to evaluate it, seems to be the reversal of a modern trend in the field of hydraulics—that is, finding a mathematical relation for a theoretical analysis developed from basic physical principles and observations. In the selection of such a function, there is no assurance that it will apply in any other instance since there is no theoretical basis for its selection. The only attribute of this alternate equation is that it does provide a function of higher degree and possibly can be used as the basis for designing an electrical circuit. Inasmuch as routing is an approximation, it is likely that, where the data indicated that a rather complex curvilinear

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[10] "Translatory Waves in Natural Channels," by J. H. Wilkinson, *Transactions*, ASCE, Vol. 110, 1945, p. 1203.

relation existed, the relation could be simulated by a series of connected straight lines. Such an assumption would necessitate a change in the value of K, and possibly x, at each break, that would hold to the next break. If these discontinuity points occur at about the same flow values for a given reach or basin, the instrument could be stopped when those points are reached, as indicated by some index such as weighted flow. Then the new K-values and x-values could be placed on the circuit, and routing could be continued.

It is quite likely that the effect of slope in the Wolf Creek Dam to Celina reach will explain one of the reasons why the Muskingum equation is not satisfactory for this reach. The discharge ratings for the ends of this reach are rate-of-change ratings which, in themselves, are tacit admissions of the slope effect of the reach and typify, to a lesser degree, conditions in many reaches in the Tennessee Valley.

Mr. Kohler is to be commended because he has found instances where the original circuit did not provide the accuracy desired; he has taken steps to find the cause, and has offered a solution rather than make a broad claim that the present circuit will apply anywhere.

Opportunity for Future Research.—In June, 1951, the USWB established an electronic stream-flow routing analog, with its operators, near the central offices of the TVA water-control staff in Knoxville, Tenn. In the continued excellent cooperative program which has been in existence since early 1940 between the TVA and the USWB, this analog is being utilized wherever applicable. It is hoped that the experience with the stream flows and characteristics of the TVA system will serve as a basis for future research to expand the usefulness of this type of analog beyond its present capabilities.

This instrument marks another milestone in the progress of developing a rapid and accurate river forecasting system. It is now produced at a relatively small cost by an instrument manufacturer. Therefore, it is not untimely to suggest that much testing of it beyond the available time, personnel, and funds of the USWB could be undertaken by other federal and state agencies and private concerns engaged in water utilization. Inasmuch as there is no large monetary return for those who develop instruments of this nature, it is unlikely that they will be developed or experimented with other than by those engaged in related work. Within these various organizations are personnel who have also the talents and experience to add to the usefulness of such instruments. These investigations would be analogous to discussions of technical papers. Some may result in modifications of the original ideas which would be definite improvements. An example is the distribution graph proposed by the late Merrill Bernard,[11] M. ASCE, which was a variation on the unit hydrograph proposed by LeRoy K. Sherman,[12] Hon. M. ASCE.

Those who persist in regarding with skepticism the analogy of flow of a true fluid and that of an electrical current should note that, even as only a first trial, the similarity of relations will accelerate many exploratory investigations, and at a reduced cost. Then, the final result can be tested under actual flow conditions.

[11] "An Approach to Determinate Stream Flow," by Merrill Bernard, *Transactions*, ASCE, Vol. 100, 1935, p. 347.

[12] "Streamflow from Rainfall by the Unit-graph Method," by LeRoy K. Sherman, *Engineering News-Record*, Vol. 108, 1932, p. 501.

C. O. Clark,[13] A. M. ASCE.—In applying an electrical circuit to the problem of flood routing, Mr. Kohler demonstrates again that much of the mechanics of hydraulic flow is similar to the mechanics of electrical flow, and, therefore, that an electrical model may indicate the answers to problems which might otherwise be sought in a hydraulic model. His electronic analog is an electrical model; he has applied it to part of the hydraulic problem of flow in open channels. His electrical model, besides being cheap enough to use where a hydraulic model would be prohibitively costly, is clean, dry, compact, and silent. Thus, it is usable in an office instead of a laboratory.

The results appear promising. The possibilities outlined, of applying the electrical model to two or more sources of inflow, are even more promising because, in these fields, manually applied mathematics fails for lack of time and labor, and taxes the mental capacity of those who try it. However, the electric analog solves only a part of the physical problem. The entire hydraulic problem may have an analog both in an hydraulic model and in an electrical one, but the physical significance, or the physical prototype, of that portion of the flow problem solved by the electrical device is not yet recognizable in nature—that is, both the hydrograph transposition with respect to time, which Mr. Kohler calls "lagging effective rainfall," and the subsequent hydrograph attenuation accomplished by the electrical circuit, are aspects of the same physical phenomenon. In nature the physical division of the two aspects does not exist. In his logical process, a man is able to simulate what does happen by two simple logical steps. One of the steps is transposition, translation, or lagging—that is, change with respect to time but without change in form or shape. The second step is attenuation, that is, flattening and lengthening—a definite change in form.

By trial and error it has been shown that a proper combination of these two steps can be satisfactory for many computational purposes. It is important, however, to recognize that both transposition and attenuation are manifestations of the existence of storage capacity (volume) along a waterway which has flow-carrying capacity (discharge), and that, for some physical reason, the waterway and the storage space are associated in such a way that when one increases so does the other.

There appears to be an appreciable time lag, or delay in flow, only because there is storage capacity. There is storage capacity in a very tangible form, in which the water which has not been passed is being stored at any given moment. Much of this storage capacity is in the channels themselves; but much of it is also in the swamps and low ground that has overflowed adjacent to the waterway. Changes in this volume are continually being made as men build levees around (or drain) the flood plain areas, either decreasing the storage capacity, or increasing the flow capacity, and thereby decreasing the combination which shows itself as a time delay in flow.

To illustrate: In Fig. 3, the "time of concentration" of this area is portrayed as 24 hr. This means that, when a steady flow rate is established from one end of the watershed to the other, there are 2 acre-ft of water in storage in the waterway, and along it, for every unit of flow of 1 cu ft per sec;

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[13] Hydr. Engr., Corps of Engrs., Southwestern Div., Tulsa, Okla.

or, if the flow is steady from each point in the watershed to the outlet, there is about 1 acre-ft of water in storage in the waterways of that watershed for each unit of flow at the outlet point.

This much storage was accounted for by the transposition, "lagging of effective rainfall," in Mr. Kohler's presentation. A much smaller amount of storage is then accounted for by the electrical machine in the routing process of attenuation. Mr. Kohler has indicated that some of the precedent for these two processes of modification, or flood routing, was in the work of the writer[6]; the writer found it in much older work. The logical ease with which one can comprehend transposition of flow will always be an adequate reason for thinking in terms of "time of concentration." Experience built up in these terms can thus be the yardstick for thinking and remembering about what really happens.

This yardstick has two corrections: (1) For the flattening or attenuation effect of storage with which the author deals, and which is computed by the machine, and (2) for the fact that the time elements are not altogether constant. Thinking about storage capacity along the stream helps to make the second correction. If the relation of that storage to the channel is such that, at all stages, there is a constant ratio of stored water to the flow capacity, there can be nearly constant time elements in small and large floods. If the capacity is always available and remains the same, it may produce the same time elements from year to year.

Although these time elements may appear to be constant (and most engineers assume they are), it is a convenient approximation of what is not exactly true. The channel flow capacity can be changed; it frequently is. The storage capacity can be changed, by either scouring the bed or breaking levees during a given flood, or by erecting levees between floods. The constant relationship between storage and discharge capacities, essential to the Muskingum theory of routing (Eq. 4), to "time of concentration" concepts, to unit hydrograph, and to many seasoned mathematical devices for understanding flood flow, does not exist in any natural channel; but, in many cases, it is a surprisingly good approximation of the composite of valley sections and of the heterogeneous obstructions which all together make up many flow channels.

However, the fact is that large floods sometimes move with unanticipated speed, also, that second floods on top of earlier large ones move even more rapidly in channels already full. Streams that increase their flow capacity by bottom scour, instead of by rising in the channel, store so little water as they change flow that the time of travel is always less than anticipated by those educated in the writings about more orthodox waterways. Finally, some streams have their storage capacity distributed in such odd ways that the net result is not to flatten the wave peak, but to build it up—not to flatten the recession part of the hydrograph, but to steepen it.

What the phenomena are, and how they are changing, can be known from the storage and discharge relationships that exist along the channel. If the conditions that exist do fit (and continue to fit) the mathematics set forth for

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[6] "Storage and the Unit Hydrograph," by C. O. Clark, *Transactions*, ASCE, Vol. 110, 1945, pp. 1419-1488.

the solution, the electronic computing device will be of inestimable aid to routine computations. Woe be to anyone who believes, without investigation, that these relationships are inherent, universal, unchanging, or unchangeable! Woe be, also, to the rising group of nontechnical managers who accept from a machine the mechanical solutions to equations they would not understand as answers to problems that even the maker of the machine could not know!

Mr. Kohler has made an outstanding contribution in developing the principle that an electric circuit can be devised to solve the simpler calculation problems of flood prediction. It opens a wide door. Through that door may very soon walk the man who will model an entire river system, with wire conduits for channels, resistances, and capacitances combining to synthesize the frictional factors and flood plain storage in whatever relation fits a particular river system. The flood hydrographs will be predicted by operating such a model forward from runoff that has been estimated from rainfall. Then, running the model backward from the early parts of the developing hydrographs, it is possible to determine more closely the real volume of runoff that appears to be causing the floods, and thereby to improve the predictions. Each of the foregoing steps can be made with a speed and precision not possible with currently available mechancial computing machines. A new day is dawning in the mechanics of nonsteady flow in open channels.

MAX A. KOHLER,[14] A. M. ASCE.—It is agreed, as Mr. Cooper states (under the heading, "Deficiencies of Router in Multiple-Purpose Reservoir Operations") that

> "*** it would increase the accuracy of the results if the factors K and x could be varied since these items, usually, do not remain constant throughout the range from low to flood flows."

Such variations would, in many cases, overcome the deficiencies of the Muskingum equation. Although the values of K and x can be changed at any time during a routing operation with the analog, by simply changing the resistances, surges of current will cause minor discontinuities in the outflow hydrograph which then must be smoothed by sketching. The use of Eq. 5 yields results similar to the varying of K and x. This is demonstrated by the fact that for steady-state conditions—that is, with $I = 0$—the storage-flow relationship is curvilinear, as shown in Fig. 6(*b*).

Another technique has been developed for applying the analog to areas in which the Muskingum equation is not completely applicable. This technique involves a separation of the inflow into two parts—one representing within-bank flows, and the other, over-bank flows. In this manner, proper values of K and x for each type of flow can be used. This technique becomes even more applicable if the value of either K or x, or both, used for the over-bank flow, is made a function of the inflow peak.

As stated in the paper, apparent deficiencies in the results obtained by using the Muskingum equation occasionally occur, since the extent of the application is excessively long. Under these circumstances, multiple routing will improve the results, but the time required for the operation will be in-

[14] Chf., Research Hydrologist, Weather Bureau, U. S. Dept. of Commerce, Washington, D. C

creased accordingly. Similar results can be obtained in a shorter period of time by lagging the inflow hydrograph and then by routing it with appropriate values of K and x.

Mr. Clark states that both the Muskingum equation and the unit hydrograph concept assume constant time elements; that is, a constant relation between storage and discharge capacity had been assumed. The simulation of the hydrograph by routing effective rainfall, as described in the paper, is based on this premise. This simulation can be used to develop unit hydrographs for any specified runoff distribution, or even for partial area unit hydrographs.

Flow routing analogs have been installed in each of the river forecast centers of the USWB. Forecasting procedures utilizing the analogs are being developed as rapidly as possible. The unit at Knoxville, is prepared to make forecasts of natural flow at selected points in the Tennessee River Basin. This unit is also engaged in further development work.

The officials of the USWB still hold the opinion that more accurate forecasts can be made in less time if the circuit of the analog can be modified to accommodate a more complex storage-flow function. To study this modification, a cooperative project is now (1953) being undertaken at Stanford University, at Stanford, Calif. This investigation is under the direction of Ray K. Linsley, A. M. ASCE.

Corrections for Transactions.—The illustration which appears as Fig. 4 and is entitled "Fig. 4.—Routed and Observed Hydrographs for the Potomac River near Washington, D. C." should be placed in the position of the present Fig. 9 and entitled "Fig. 9.—Storage Function for Verdigris River Above Independence, Kans.," and vice versa.

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